A STUDY OF THE HEAVY MINERALS FROM TWO SECTIONS OF THE BEREA SANDSTONE IN NORTHEASTERN OHIO

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for the Degree Bachelor of Science
in Geology and Mineralogy

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ACKNOWLEDGEMENTS

I would like to especially thank Professor George E. Moore Jr., who suggested the topic and provided invaluable assistance and criticism in the heavy mineral study and writing this thesis. I would also like to thank Professor Kenneth O. Stanley for use of his laboratory equipment and Mr. Robert Wilkinson for his aid in the photomicrography.

INTRODUCTION

The purpose of this investigation was to study the heavy mineral fraction of the rocks from two sections of the Berea sandstone in northeastern Ohio.

This study involved the examination, with the petrographic microscope, of grain mounts prepared from heavy mineral grains separated from the disaggregated sand from samples of the two sections. The types, characteristics, and the intrasectional and intersectional relationships of the heavy mineral grains were determined, and conclusions as to the significance of these factors were reached.

THE BEREA SANDSTONE

The Berea sandstone is Kinderhookian (Lower Mississippian) in age; it crops out in eastern Ohio, western Pennsylvania, western West Virginia, and eastern Kentucky. The Berea sandstone was deposited in two stages between the underlying marine Bedford shale and the overlying marine Sunbury shale. The first depositional stage resulted in a subaerial delta and the second stage in a subaqueous (marine) pavement that formed when a transgression of the sea occured (Pepper, DeWitt and Demarest, 1949).

SAMPLING AND PREPARATION

The two sections sampled are from outcrops of the Berea in tributary ravines of the Chagrin river in the townships of Kirtland (southwestern Lake County) and Chester (northwestern Geauga County), Ohio (Figure 1). Both sections

are from rocks deposited during the second stage of Berea sedimentation. Table 1 shows the lithologic descriptions of the sections.

Each bed of the respective sections was sampled, with rocks being taken laterally as well as vertically along the outcrop. This was done to avoid the possibility of collecting rocks that contained local concentrations of mineral species, which would consequently bias the results of the study.

After collecting, the samples were mechanically disaggregated; care was taken not to fracture the individual grains. The samples were then reduced in volume for laboratory work by using a sample splitter. The samples were then sieved, with the grains between 60 and 80 mesh (referred to as 80 in this paper) and between 100 and 120 mesh (referred to as 120 in this paper) being used for study. The grains were highly stained with iron oxide and it was necessary to treat them with a heated solution of stannous chloride and hydrochloric acid to remove the stain, the procedure being repeated until the grains were clean.

After cleaning, the heavy mineral fraction was separated from the light fraction by floatation using bromoform (specific gravity 2.884). The apparatus used consisted of two funnels, one above holding the bromoform with a stopped rubber hose on the spout leading to the funnel below, which held filter paper and lead into a beaker for recovery of the bromoform. With the rubber hose stopped

the sand grains were sprinkled into the upper funnel, holding the bromoform; the heavy mineral grains sank to the stop in the rubber hose. After all the heavy grains had settled, the stop was released permitting the heavy mineral grains to be washed into the filter paper in the lower funnel. The heavy grains were then washed with acetone to remove the bromoform on them and also the bromoform which had been absorbed by the filter paper.

After separation, the heavy and light mineral grains were mounted on standard petrographic slides with Canada balsam and were ready for study (see Table 2 and appendis for heavy mineral counts and descriptions, respectively).

FIGURE 1.

Outcrop Map and Sections Sampled of the Berea Sandstone

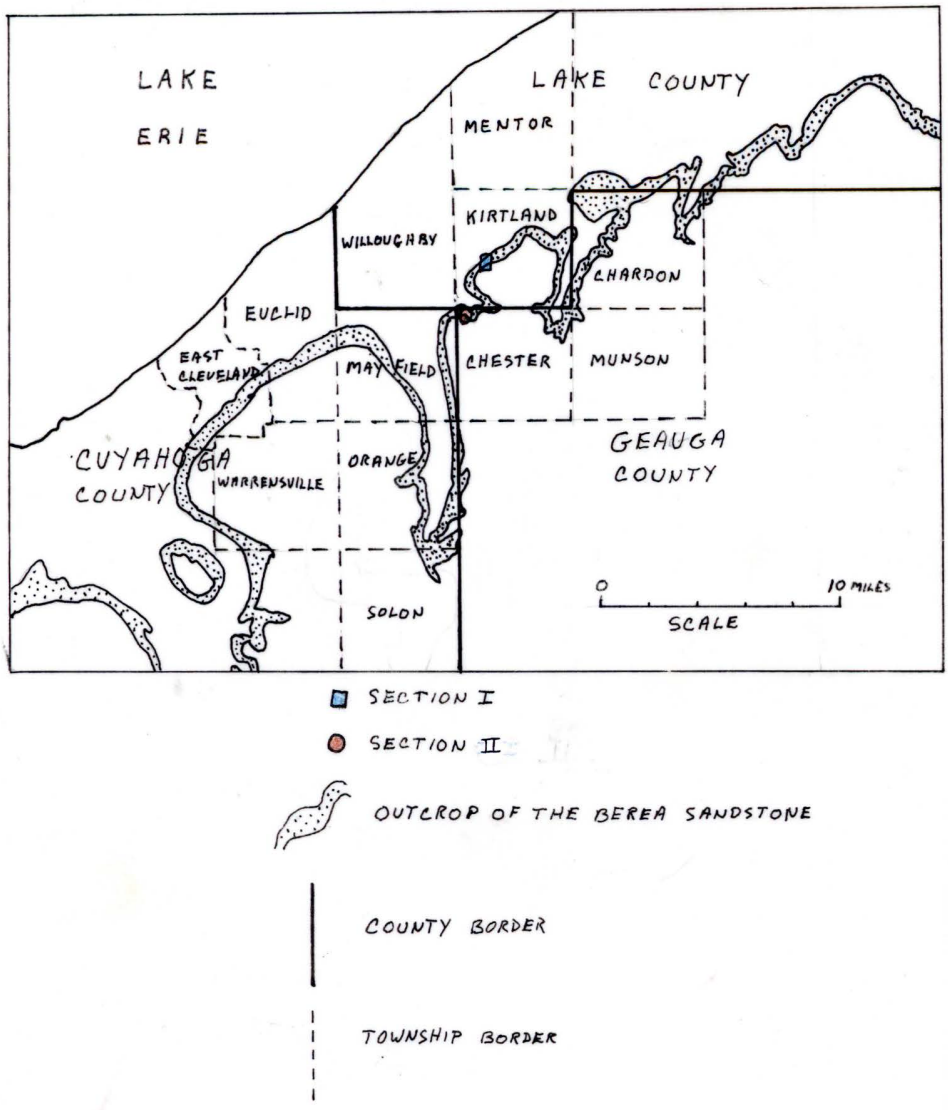


TABLE 1

Measured Sections of the Berea Sandstone

Section I

Unit		Thickness
I/5	Fine-grained, buff, weathers brown, cross-bedded, well indurated, silty sandstone. Rock is stained with swirled streaks of iron oxide.	19'4"
I/4	Fine-grained, yellow-tan, strongly crossbedded, friable sandstone. Rock breaks easily along crossbedding. Top of bed has prominent oscillation ripple marks.	8'8"
I/3	Fine-grained, gray, weathers dark red-brown, friable, silty sandstone.	3'
I/2	Fine-grained, buff to gray, weathers yellow-tan, well-indurated, silty sandstone.	7'
I/1	Fine-grained, light buff, weathers red-brown, friable, massive sandstone. Weathered portions of rock contain prominent spots of iron oxide.	3'1"
	Total thickness of section I:	41'1"

Section II

II/7	Medium to fine-grained, buff, well indurated, crossbedded sandstone. Rock readily breaks along crossbedding.	5'
II/6	Fine-grained, gray, weathers yellow, well indurated crossbedded sandstone. Rock shows soft sediment slumping.	4'4"
II/5	Fine-grained, gray to buff, laminated, silty sandstone. Rock shows prominent fracturing	

TABLE 1 cont.

	along the surfaces of laminae in the lower 1/3 of the bed.	6'3"
II/4	Medium to fine-grained, buff, well indurated, cross-bedded sandstone. The surface of the rock is differentially weathered.	5'
II/3	Medium to fine-grained, gray to buff, crossbedded, sandstone. The top of unit is a 0.25 inch thick layer of highly ferruginous, highly mudcracked sandstone.	3'6"
II/2	Medium to fine-grained, gray to buff, crossbedded sandstone. About half of the rock adjacent to crossbed surfaces is hematite-rich; this half is more resistant to weathering and consequently the rock shows prominent differential weathering.	9'6"
II/1	Fine-grained, light buff, weathers dark red-brown, friable, silty sandstone.	11'
	Total thickness of section II :	44'7"

TABLE 2

UNIT, SIZE OF GRAINS, NUMBER OF GRAINS COUNTED	NUMBER OF GRAINS OF RESPECTIVE MINERAL SPECIES AND PERCENT OF TOTAL GRAINS COUNTED PER UNIT + ALL SAMPLES CONTAINED LESS THAN 1 PERCENT HEAVY MINERAL GRAINS BY WEIGHT											
	LEUCOXENE	HEMATITE	RUTILE (INCL. ORTHITE) & ANATASE	TOURMALINE	PYRITE	ZIRCON	MONAZITE	ILMENITE-MAGNETITE	MUSCOVITE	BIOTITE	GARNET	AUTHIGENIC GRAINS *
I/1 (80)- 176	44 - 25%	40 - 22.7%	0	10 - 5.7%	69 - 39.2%	2 - 1.1%	0	3 - 1.7%	3 - 1.7%	0	0	5 - 2.8%
I/1 (80)- 905	339 - 37.4%	77 - 8.5%	10 - 1.1%	161 - 17.8%	231 - 25.5%	22 - 2.4%	0	16 - 1.8%	0	0	0	53 - 5.8%
I/2 (80) - 298	57 - 19.1%	41 - 13.8%	1 - 0.3%	25 - 8.4%	85 - 28.5%	3 - 1%	0	11 - 3.7%	0	0	0	25 - 8.4%
I/2 (120) - 664	207 - 31.2%	34 - 5.1%	4 - 0.6%	111 - 16.7%	160 - 24%	23 - 3.5%	0	43 - 6.5%	1 - 0	10 - 1.5%	0	35 - 5.3%
I/3 (80) - 87	28 - 32.2%	9 - 10.3%	0	13 - 14.9%	26 - 29.9%	1 - 1.1%	0	8 - 9.2%	0	2 - 2.3%	0	0
I/3 (120) - 639	178 - 27.8%	25 - 3.5%	7 - 1.1%	77 - 12.1%	87 - 13.6%	87 - 13.6%	0	29 - 4.5%	55 - 8.6%	7 - 1.1%	0	53 - 8.3%
	MOUNTS OF UNIT I/4 UNFIT FOR STUDY											
I/5 (80) - 101	44 - 43.6%	8 - 7.9%	4 - 3.9%	12 - 11.9%	13 - 12.9%	3 - 3%	8 - 7.9%	9 - 8.9%	0	0	0	0
I/5 (120) - 358	186 - 51.9%	3 - 0.6%	3 - 0.6%	52 - 14.5%	17 - 4.7%	10 - 2.8%	23 - 6.4%	23 - 6.4%	13 - 3.6%	1 - 0.3%	0	19 - 5.3%
II/1 (80) - 306	139 - 45.4%	4 - 1.3%	7 - 2.3%	6 - 2%	100 - 32.7%	6 - 2%	4 - 1.3%	9 - 2.9%	8 - 2.6%	1 - 0.3%	0	10 - 3.3%
II/1 (120) - 594	120 - 20.2%	8 - 1.3%	15 - 2.5%	44 - 7.4%	302 - 50.8%	24 - 4%	26 - 4.4%	13 - 2.2%	36 - 6.1%	0	6 - 1%	0
II/2 (80) - 411	214 - 52.1%	0	0	123 - 29.9%	10 - 2.4%	3 - 0.7%	2 - 0.5%	36 - 8.8%	11 - 2.8%	1 - 0.2%	0	12 - 2.8%
II/2 (120) - 515	220 - 42.7%	28 - 5.4%	14 - 2.7%	122 - 23.7%	6 - 1.8%	35 - 6.8%	2 - 0.4%	25 - 4.8%	28 - 5.4%	0	6 - 1.2%	29 - 5.6%
	MOUNTS OF UNIT II/3 UNFIT FOR STUDY											
II/4 (80) - 174	51 - 29.3%	7 - 4%	6 - 3.4%	29 - 16.7%	12 - 6.9%	2 - 1.1%	0	0	9 - 5.2%	8 - 4.6%	0	50 - 28.7%
II/4 (120) - 390	151 - 38.7%	17 - 4.4%	11 - 2.8%	66 - 16.9%	5 - 1.3%	10 - 2.6%	0	14 - 3.6%	11 - 2.8%	0	0	105 - 26.9%
II/5 (80) - 76	20 - 26.3%	18 - 23.7%	1 - 1.3%	9 - 11.8%	9 - 11.8%	2 - [illegible]	1 - 1.3%	5 - 6.6%	1 - 1.3%	0	3 - 3.9%	10 - 13.2%
II/5 (120) - 480	254 - 52.9%	42 - 8.8%	8 - 1.7%	51 - 10.6%	0	33 - [illegible]	0	4 - 0.8%	1 - 0.2%	0	3 - 0.6%	77 - 16%
II/6 (80) - 183	92 - 50.3%	2 - 1.1%	4 - 2.2%	34 - 18.6%	8 - 4.4%	3 - [illegible]	2 - 1.1%	14 - 7.6%	13 - 7.1%	0	0	11 - 6%
II/6 (120) - 399	178 - 47%	0	11 - 2.9%	92 - 24.3%	3 - 0.8%	9 - 2.4%	0	17 - 4.5%	11 - 2.9%	0	0	58 - 15.3%
II/7 (80) - 131	73 - 56.7%	11 - 8.4%	6 - 4.6%	21 - 16%	2 - 1.5%	3 - 2.3%	0	2 - 1.5%	0	0	6 - 4.6%	7 - 5.3%
II/7 (120) - 609	360 - 59.1%	13 - 2.1%	30 - 4.9%	107 - 17.6%	1 - 0.2%	23 - 3.8%	0	14 - 2.3%	2 - 0.3%	0	24 - 3.9%	35 - 5.7%

* DEFINED BY THE AUTHOR AS THOSE GRAINS THAT ARE COMPOSED PREDOMINANTLY OF AUTHIGENIC TITANIUM MINERALS AND MAY CONTAIN LEUCOXENE, BUT IN AN AMOUNT NOT EXCEEDING 50 PERCENT OF THE GRAIN

FIGURE 2

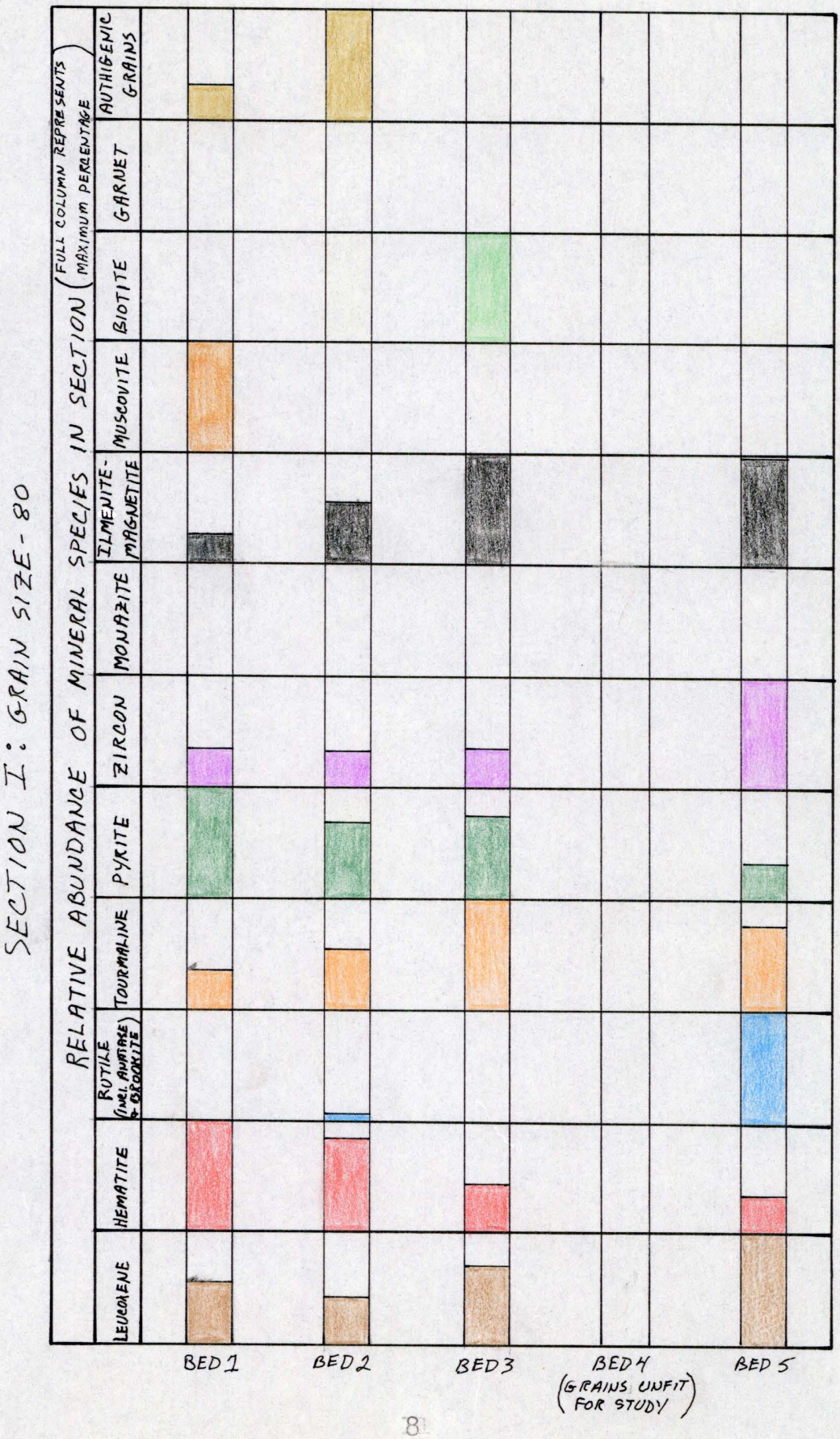

SECTION I: GRAIN SIZE - 80
RELATIVE ABUNDANCE OF MINERAL SPECIES IN SECTION (FULL COLUMN REPRESENTS MAXIMUM PERCENTAGE)
LEUCOXENE
HEMATITE
RUTILE (INCL. ANATASE & BROOKITE)
TOURMALINE
PYRITE
ZIRCON
MONAZITE
ILMENITE-MAGNETITE
MUSCOVITE
BIOTITE
GARNET
AUTHIGENIC GRAINS
BED 1
BED 2
BED 3
BED 4 (GRAINS UNFIT FOR STUDY)
BED 5

FIGURE 3

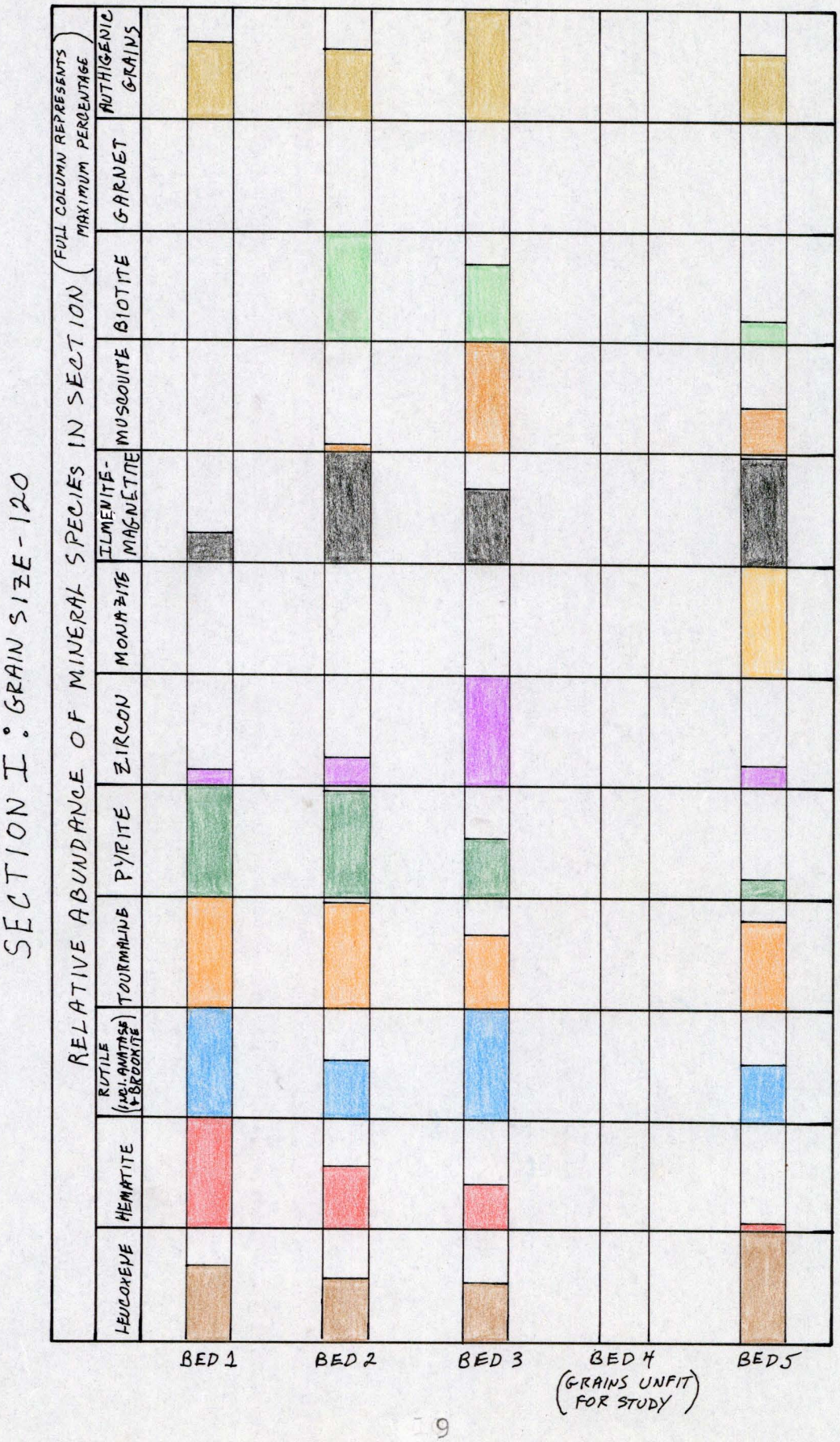

SECTION I : GRAIN SIZE - 120
RELATIVE ABUNDANCE OF MINERAL SPECIES IN SECTION (FULL COLUMN REPRESENTS MAXIMUM PERCENTAGE)
LEUCOXENE
HEMATITE
RUTILE (INCL. ANATASE & BROOKITE)
TOURMALINE
PYRITE
ZIRCON
MONAZITE
ILMENITE-MAGNETITE
MUSCOVITE
BIOTITE
GARNET
AUTHIGENIC GRAINS
BED 1
BED 2
BED 3
BED 4
(GRAINS UNFIT FOR STUDY)
BED 5

FIGURE 4

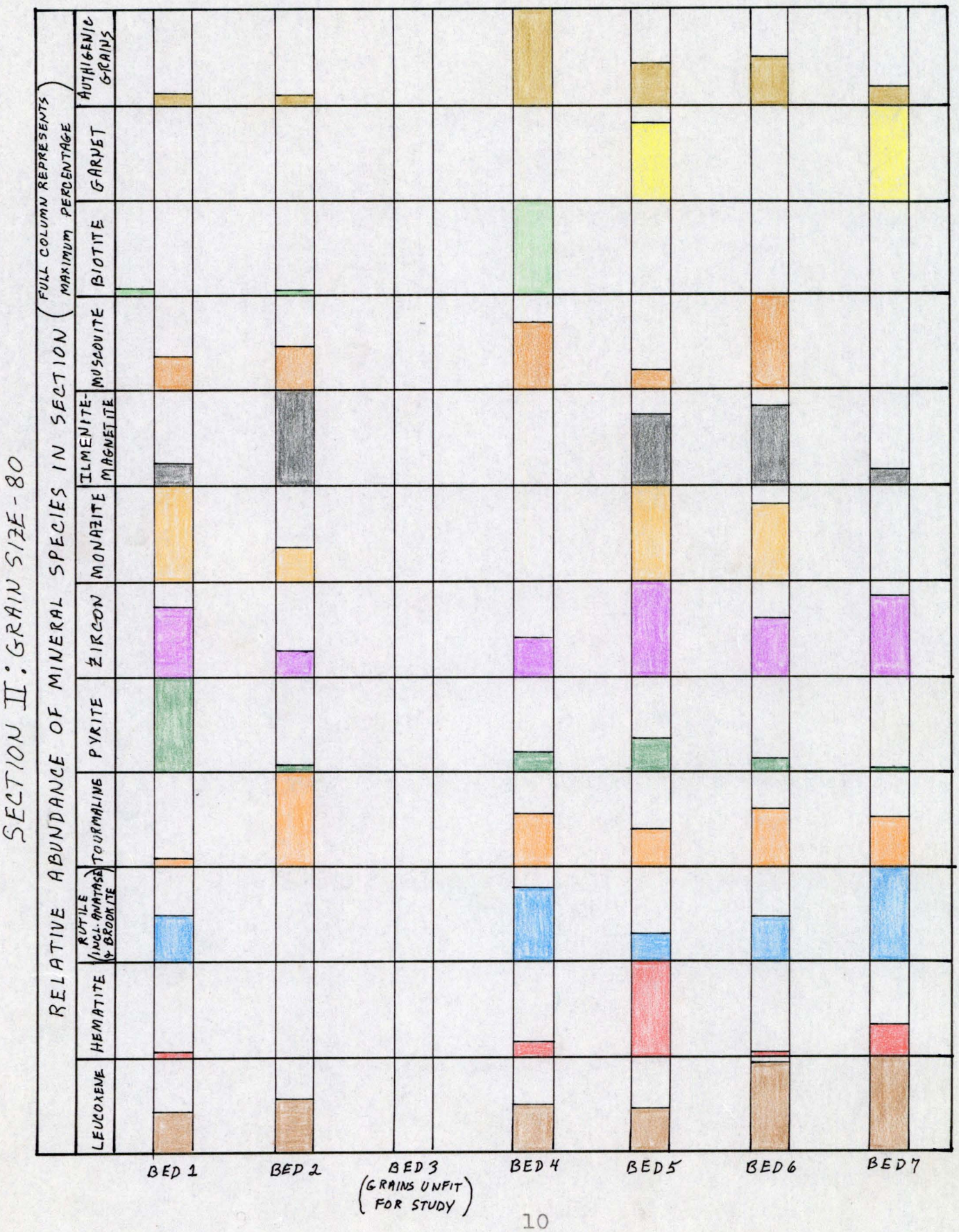
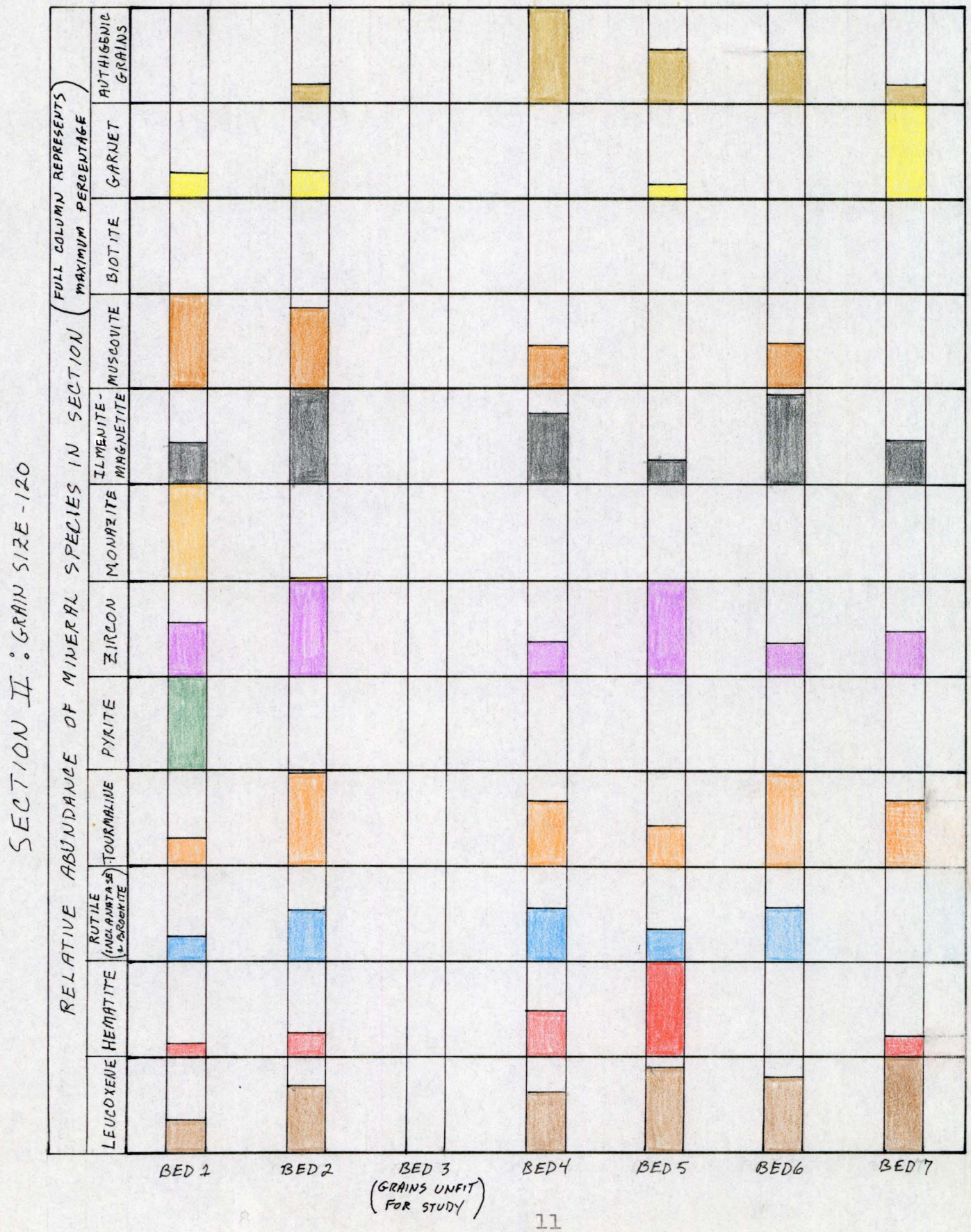

SECTION II: GRAIN SIZE - 80
RELATIVE ABUNDANCE OF MINERAL SPECIES IN SECTION (FULL COLUMN REPRESENTS MAXIMUM PERCENTAGE)
LEUCOXENE
HEMATITE
RUTILE (INCL. ANATASE & BROOKITE)
TOURMALINE
PYRITE
ZIRCON
MONAZITE
ILMENITE-MAGNETITE
MUSCOVITE
BIOTITE
GARNET
AUTHIGENIC GRAINS
BED 1
BED 2
BED 3 (GRAINS UNFIT FOR STUDY)
BED 4
BED 5
BED 6
BED 7

FIGURE 5


SECTION II : GRAIN SIZE - 120
RELATIVE ABUNDANCE OF MINERAL SPECIES IN SECTION
(FULL COLUMN REPRESENTS MAXIMUM PERCENTAGE)
LEUCOXENE
HEMATITE
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GARNET
AUTHIGENIC GRAINS
BED 1
BED 2
BED 3
(GRAINS UNFIT FOR STUDY)
BED 4
BED 5
BED 6
BED 7

INTERPRETATIONS OF THE HEAVY MINERAL GRAIN STUDY

Microscopic study of the heavy mineral grains of the two selected sections of the Berea sandstone reveals that considerable authigenic mineral formation took place in the Berea.

The pyrite, in all of the grain mounts, has perfect (euhedral) crystal form and at least a portion of the grains in each mount have sand grain impressions. These two factors clearly indicate an authigenic origin. Authigenic pyrite is most characteristic of very fine-grained organic-rich sediments eg. shales and mudstones, whereas the Berea is considered a mature sandstone. However the Bedford shale, underlying the Berea sandstone, consists predominately of shales and siltstones, has a relatively abundant organic content, and contains pyrite (Pepper, DeWitt and Demarest, 1949).

Migration of sulfide-rich fluids from the Bedford shale may account for the pyrite in the Berea. Further evidence for this hypthesis is the general decrease in the percent of pyrite per bed upsection from the base of the Berea (Table 2), Figures 2, 3, 4, and 5)

The crystals on the leucoxene grains also appear to be authigenic, the evidence being their euhedral form. Leucoxene is an amorphous in situ decomposition product of ilmenite or titaniferous magnetite, and is a form of titanium dioxide (Milner, 1962). The association of the

crystals suggests that they formed from the recrystalization of leucoxene and hence are also a form of titanium dioxide (eg. rutile, anatase, brookite).

Those grains listed in Table 2 as 'authigenic grains' consist of the same minerals as the crystals on the leucoxene grains. These grains also appear to have been formed by the recrystallization of leucoxene, the evidence being the presence of leucoxene in many of the grains.

The subangular tourmaline grains are also believed to be authigenic (the portion that appears to be an overgrowth). The anomalous angularity, crystal faces, and striations on the grains serve as evidence. Stow (1932) described authigenic tourmaline in the Devonian Oriskany sandstone, which is similar to the Berea.

Quartz overgrowths on the pyrite, leucoxene, 'authigenic grains', hematite, and ilmenite-magnetite grains suggest a period during which silica-rich pore fluids fluids existed and geochemical conditions were favorable for the precipitation of quartz. Since the quartz overgrowths appear on the 'authigenic grains' and on pyrite, the deposition of the quartz occured after the formation of these authigenic minerals.

It is also evident that in situ alteration of ilmenite (or titaniferous magnetite) to leucoxene, and pyrite to hematite, occured. The subangular platy hematite grains are either detrital or fragments of the iron oxide concentrations in the sandstone, which formed during the mechanical disaggregation of the rock samples.

The predominance of rounded to well-rounded, and highly fractured grains of resistant minerals suggests that the majority of the sediment in the Berea sandstone has undergone at least two cycles of erosion and deposition. The occasional euhedral zircons, and the relatively unaltered biotite and garnet suggest that there was an occasional or minor influx of material that was derived from a primary source or from sediments which had undergone only one cycle of erosion and deposition.

In general, from Table 2, and Figures 2,3,4, and 5, the heavy mineral suites from the two sections are essentially the same. One notable difference is the absence of garnet from Section I, whereas it does occur occasionaly in section II, Monazite is also absent in Section I, except for the youngest bed. The lack of these minerals from Section I may be explained by the grains being localized ie. rocks containing these minerals were missed during sampling, or the minerals were never deposited.

The pyrite in Section I appears to decrease in abundance rather uniformly upsection (Table 2, and Figures 2, and 3), whereas the pyrite in Section II appears to decrease more abruptly upsection.(Table 2, and Figures 4, and 5). A possible explanation for this is that there was a restriction of sulfide-rich fluid migration into the upper beds of Section II, whereas in Section I, the migration of sulfide-rich fluids decreased uniformly upsection. Another possible explanation is that in section II

there was a limited amount of iron present in the younger beds, in which case only a limited amount of pyrite could be formed, whether or not sulfide-rich fluids could migrate freely.

CONCLUSIONS

The types of the detrital heavy mineral grains, and their characteristics, from the two sections of the Berea sandstone give evidence that the Berea is a physically and chemically mature sandstone.

The presence of leucoxene, in particular the leucoxene present on ilmenite (titaniferous magnetite), and hematite pseudomorphs of pyrite give evidence of in situ alteration of minerals that were susceptible to alteration.

The presence of the authigenic titanium minerals, euhedral pyrite crystals with sand grain impressions, and quartz overgrowths on grains gives evidence that at certain times in the diagenetic history of the Berea sandstone, conditions existed that were favorable for the formation of these minerals. However the time of formation of these minerals was not necessarily synchronous as is evident from the quartz overgrowths on the authigenic titanium mineral grains and on pyrite.

With a few exceptions the heavy minerals in the two sections are the same, and it seems likely that the sources of sediment, and diagenetic processes that occured in the two sections are the same.

APPENDIX

Description of Heavy Mineral Grains

Unit-Grain Size	
I/1-(80)	Leucoxene: Rounded equant or elongate to subrounded grains. Grains white to light brown in reflected light. About 20 percent of grains have clusters of red authigenic crystals on surface.
	Tourmaline: Well-rounded grains, pleochroic in shades of brown, and green. About 10 percent of grains are pleochroic in both colors.
	Pyrite: Grains are single crystals or crystal aggregates. Crystals show well developed cubic or octahedral faces. About 25 percent of grains are slightly oxidized as evidenced by an iridescent tarnish in reflected light. About 30 percent of grains have sand grain impressions.
	Zircon: Well-rounded light pink highly fractured.
	Hematite: Subangular platy grains. Grains are dark red-brown in reflected light and are translucent at edges.
	Authigenic grains: Aggregates of small yellow amber or red crystals. Crystals have extreme birefringence and high refractive indices.
	Ilmenite-Magnetite: Subrounded grains, black in reflected light and with small patches of leucoxene on surface.

Muscovite: Flat grains with subrounded outlines and ragged edges. Grains have a wavy extinction.

I/1-(120) Leucoxene: Rounded equant or elongate to subrounded grains. Grains white (Figure 6) to light brown in reflected light. About 25 percent of grains have small clusters of red or amber euhedral authigenic crystals on surface.

Tourmaline: Well-rounded grains, about 25 percent having short prismatic form. Grains are pleochroic in shades of blue, brown, and green. About 30 percent of grains contain small acicular inclusions.

Pyrite: Grains are aggregates of euhedral crystals and are brass yellow in reflected light (Figure 6). About 30 percent of grains have sand grain impressions. About 25 percent of grains show varying degrees of oxidation, and about 10 percent are completely enveloped in quartz.

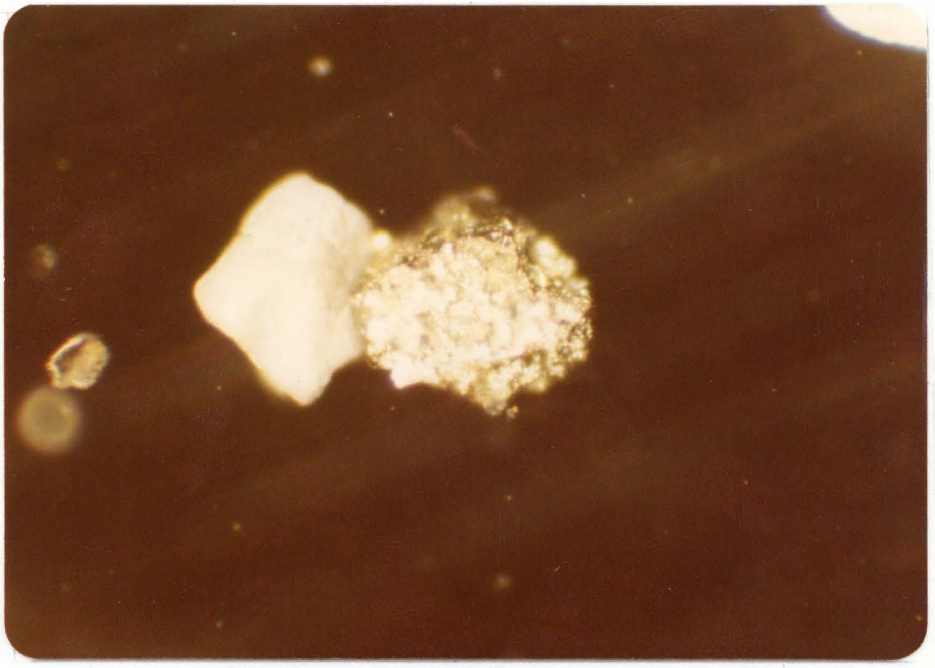
Zircon: Well-rounded to angular pink to colorless grains. Well-rounded grains are highly fractured, whereas angular grains show little or no evidence of fracturing and have terminations.

Hematite: Subangular platy grains, red-brown in reflected light and with translucent edges. About 10 percent of grains appear to be pseudomorphs of pyrite.

Ilmenite-Magnetite: Subrounded grains, black in reflected light. About 50 percent of grains have leucoxene on surface.

Authigenic grains: Aggregates of small amber or red crystals with extreme birefringence and high

FIGURE 6



Photomicrograph of leucoxene (left) and pyrite (right). Reflected light, 110X. Note sand grains impressions on pyrite. From unit I/1-(120)

refractive indices.

Rutile: Subrounded to rounded elongate grains. Grains are red or blue (anatase) and have an adamantine luster in reflected light.

I/2-(80) Leucoxene: Subrounded to rounded grains, white in reflected light. About 20 percent of grains have small clusters of red authigenic crystals on surface.

Tourmaline: Subangular to rounded grains, pleochroic in shades of green and brown to clear. Subangular grains appear to be rounded detrital grains with overgrowths of tourmaline.

Pyrite: Euhedral crystals or crystal aggregates with sand grain impressions. About 50 percent of grains are brass yellow in reflected light with the other 50 percent having an iridescent tarnish due to oxidation.

Zircon: Subrounded light pink grains with remnant terminations.

Hematite: Subangular platy grains, red-brown in reflected light, and about 10 percent of grains appear to be pseudomorphs of pyrite.

Ilmenite-Magnetite: Subrounded grains, black in reflected light. About 50 percent of grains have leucoxene along the edges.

Biotite: Unaltered flat grains with irregular outlines and ragged edges.

I/2-(120) Leucoxene: Subrounded to rounded grains, white to light brown in reflected light. About 25 percent of grains have clusters of small red authigenic crystals on surface, which have extreme birefringence and refractive indices.

Tourmaline: Subrounded to rounded grains, 10 percent of which have short prismatic form. Grains are pleochroic in shades of brown, blue, and green. About 25 percent of grains contain small acicular inclusions.

Pyrite: Euhedral crystals or crystal aggregates that are brass yellow in reflected light. About 90 percent of grains have sand grain impressions. About 25 percent of grains are completely enclosed in quartz and show no oxidation, whereas free grains show varying degrees of oxidation.

Hematite: 75 percent of grains occur as subangular and platy and 25 percent are pseudomorphs of pyrite. Both types are red-brown in reflected light, however platy grains are translucent at edges, whereas the pseudomorphs are not.

Zircon: 70 percent of grains are well-rounded and highly fractured, and 30 percent **are angular, show crystal faces, and are not fractured. Both types of grains are colorless.**

Ilmenite-Magnetite: Subrounded grains, and are extensively altered to leucoxene.

Authigenic grains: Aggregates of red, amber, and colorless crystals having extreme birefringence and high refractive indices.

Rutile: Well-rounded elongate grains; red, with an adamantine luster in reflected light.

Biotite: Flat unaltered grains with rounded to irregular outlines and ragged edges.

I/3-(80) Leucoxene: Subrounded to well-rounded grains, white to light brown in reflected light. Approximately 50 percent of grains have clusters of red authigenic crystals on surface which have extreme birefringence and high refractive indices.

Tourmaline: Subrounded to well-rounded grains. About 25 percent of grains have short prismatic form. Grains are pleochroic in shades of blue, green, and brown.

Pyrite: Euhedral crystals or crystal aggregates, brass yellow in reflected light. About 20 percent of grains are tarnished by oxidation, and 80 percent have sand grain impressions.

Zircon: Subrounded colorless grain with remnant terminations.

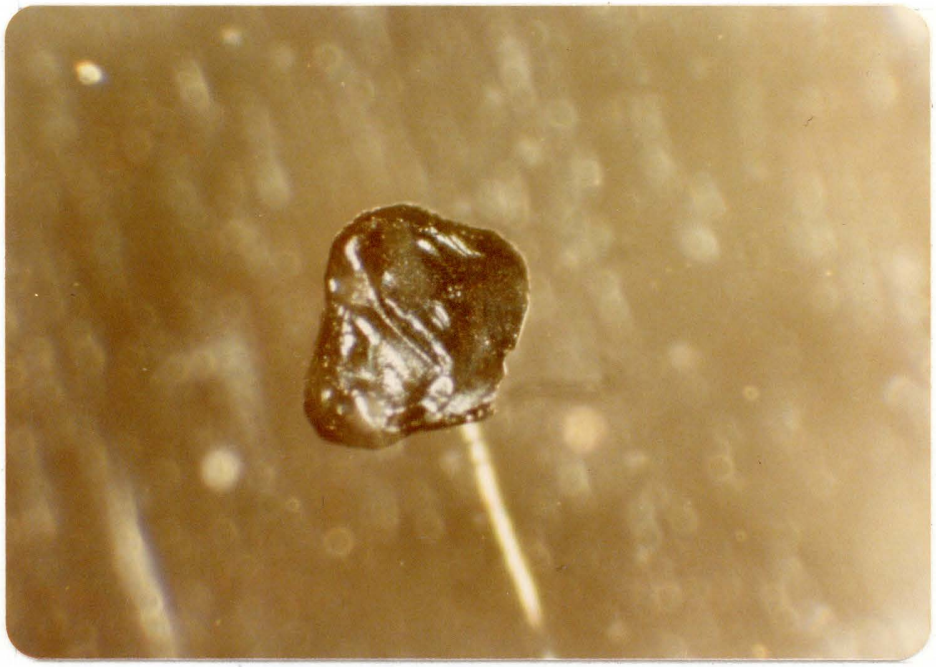
Hematite: 50 percent of grains are subangular and platy, red-brown in reflected light and translucent at edges. The other 50 percent are pseudomorphs of pyrite, completely opaque, and red-brown in reflected light.

Ilmenite-Magnetite: Subrounded grains, black in reflected light (Figure 7). About 25 percent of grains are altered in varying degrees to leucoxene.

Biotite: Flat unaltered grains with irregular outlines and ragged edges.

I/3-(120) Leucoxene: Subrounded to rounded grains, white in reflected light. About 25 percent of grains have clusters of small yellow and red authigenic crystals on surface that have extreme birefringence and

FIGURE 7



Photomicrograph of ilmenite. Reflected light, 60X. From unit I/3-(80)

high refractive indices.

Tourmaline: Well-rounded grains, pleochroic in shades of brown, blue, and green. About 10 percent of grains are pleochroic in more than one color, resulting in a mottled appearence.

Pyrite: Euhedral crystals or crystal aggregates, of which about 80 percent have sand grain impressions. About 75 percent of grains are heavily oxidized and are in part red-brown hematite, the balance are brass yellow in reflected light.

Hematite: Subangular platy grains, red-brown in reflected light.

Rutile: Well-rounded elongate grains, red, having an adamantine luster in reflected light.

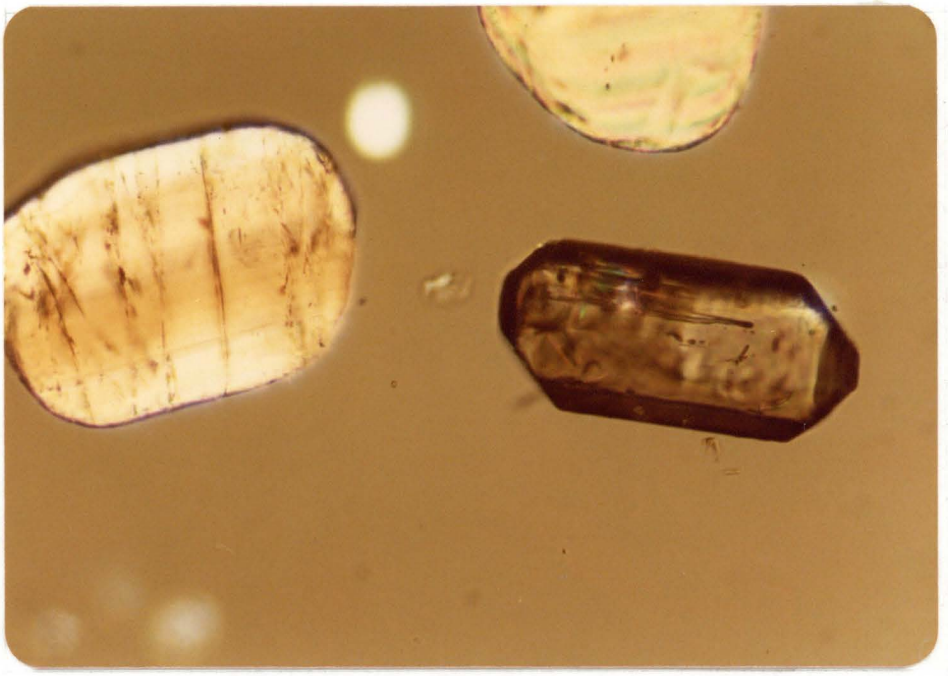
Ilmenite-Magnetite: Subrounded grains, black in reflected light; show varying degrees of alteration to leucoxene.

Zircon: 80 percent of grains are well-rounded to subrounded and are extensively fractured. 20 percent are angular, euhedral grains with few or no fractures (Figure 8). About 50 percent of euhedral grains contain small acicular inclusions.

Authigenic grains: Aggregates of red, amber or colorless crystals having extreme birefringence and high refractive indices.

Muscovite: Flat grains with rounded to irregular outlines and ragged edges. Grains have a wavy extinction.

FIGURE 8



Photomicrograph of zircon (right-center). Note euhedral form and inclusions. Grains to left and above are tourmaline. Crossed nicols, 250X. From unit I/3-(120).

I/5-(80) Leucoxene: Subrounded to rounded grains, white to light brown in reflected light. About 25 percent of grains have clusters of red authigenic crystals on surface. About 20 percent of grains have quartz overgrowths.

Tourmaline: Subrounded to rounded grains, pleochroic in shades of brown, red-brown, and green. About 25 percent of grains contain small acicular inclusions (Figure 9).

Pyrite: Aggregates of small crystals. About 75 percent of grains are brass yellow in reflected light and 25 percent have an iridescent tarnish due to oxidation.

Hematite: Subangular platy grains, red-brown in reflected light and have translucent edges.

Zircon: Well-rounded light pink highly fractured.

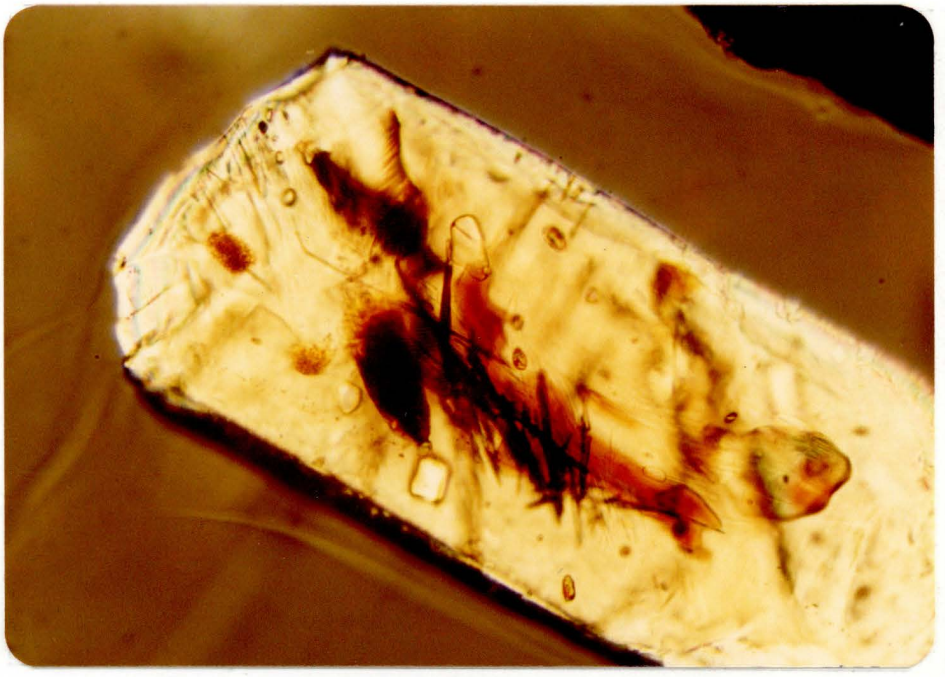
Ilmenite-Magnetite: Subangular grains, black in reflected light. About 25 percent of grains have small amber prismatic crystals on surface and about 25 percent are altered to leucoxene to varying degrees.

Monazite: Well-rounded translucent grains, yellow, have a waxy luster in reflected light.

Rutile: Well-rounded elongate grains, red, have an adamantine luster in reflected light.

I/5-(120) Leucoxene: Rounded grains, white in reflected light. About 40 percent of grains have clusters of small red authigenic crystals on surface which have extreme birefringence and high re-

FIGURE 9



Photomicrograph of tourmaline. Note acicular inclusions. Crossed nicols, 250X. From unit I/5-(80).

fractive indices. About 30 percent of grains have quartz overgrowths.

Tourmaline: Subangular to well-rounded grains. Subangular grains appear to consist of a well-rounded detrital tourmaline core with an overgrowth of authigenic tourmaline. Pleochroic in shades of green, brown, red-brown, and clear. About 25 percent of grains contain small acicular inclusions.

Pyrite: Aggregates of small euhedral crystals. About 70 percent of grains have sand grain impressions. About 75 percent of grains are brass yellow in reflected light, whereas 25 percent have an iridescent tarnish due to oxidation.

Hematite: Subangular platy grains, red-brown in reflected light and with translucent edges.

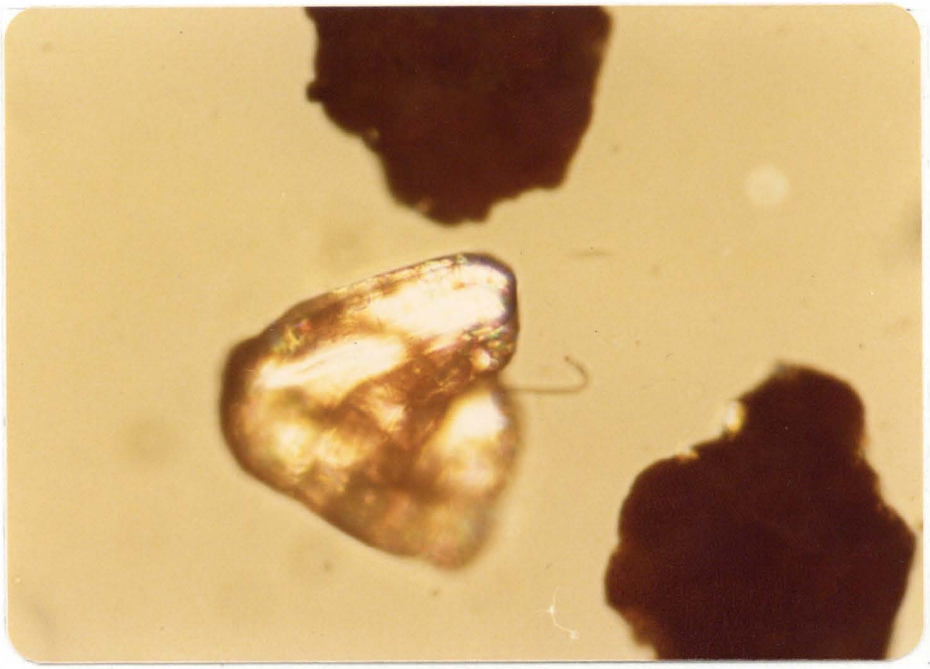
Zircon: Subrounded to well-rounded colorless to pink grains. Subrounded grains have remnant terminations. All grains are fractured, with number of fractures increasing with increasing roundness.

Ilmenite-Magnetite: Subrounded grains, black in reflected light. All grains show varying amounts of alteration to leucoxene.

Monazite: Subrounded transparent (Figure 10) to well-rounded translucent grains. Translucent grains are yellow with a waxy luster in reflected light.

Rutile: Well-rounded grains with patches of leucoxene on surface. Grains are red and have an adamantine luster in reflected light.

FIGURE 10



Photomicrograph of monazite. Crossed nicols, 250X. From unit I/5-(120).

Authigenic grains: Aggregates of small amber or red crystals. Crystals have extreme birefringence and high refractive indices.

Muscovite: Flat grains with rounded to irregular outlines and ragged edges. Grains have a wavy extinction.

II/1-(80) Leucoxene: Rounded grains, white in reflected light. About 50 percent of grains have clusters of small red authigenic crystals on surface.

Tourmaline: Well-rounded, pleochroic in shades of blue and green.

Pyrite: Aggregates of small euhedral crystals. 50 percent of grains are brass yellow in reflected light, whereas the remainder have an iridescent tarnish due to oxidation. About 40 percent of grains have impressions of sand grains.

Hematite: Subangular platy grains, red-brown in reflected light and translucent at edges.

Zircon: Well-rounded light pink and highly fractured.

Ilmenite-Magnetite: Subrounded grains, black in reflected light. About 80 percent of grains show varying degrees of alteration to leucoxene.

Rutile: Well-rounded grains, red and have an adamantine luster in reflected light.

Authigenic grains: Clusters of small amber red or colorless crystals. About 50 percent of grains contain an appreciable amount of leucoxene.

Muscovite: Flat grains with rounded outlines and ragged edges. About 50 percent of grains have

small, acicular inclusions.

Monazite: Well-rounded translucent yellow grains. Grains have a waxy luster in reflected light.

II/1-(120) Leucoxene: Subrounded to rounded grains, white to light brown in reflected light. About 40 percent of grains have clusters of red authigenic crystals on surface.

Tourmaline: Well-rounded grains, pleochroic in shades of brown, green, and blue, to clear.

Pyrite: Aggregates of small euhedral crystals, brass yellow in reflected light. About 80 percent of grains are intimately associated with quartz.

Hematite: Subangular platy grains, red-brown in reflected light and translucent at edges.

Zircon: Well-rounded light pink to clear and highly fractured.

Ilmenite-Magnetite: Subangular grains, highly altered to leucoxene.

Rutile: Subrounded to well-rounded grains, dark red, adamantine luster in reflected light.

Monazite: Well-rounded translucent yellow grains, waxy luster in reflected light.

Garnet: Subangular, yellow to light brown, highly fractured, and completely isotropic.

Muscovite: Flat grains with rounded outlines and ragged edges, wavy extinction.under crossed nicols.

II/2-(80) Leucoxene: Subrounded to rounded grains, white in reflected light. About 50 percent of grains have clusters of small amber or red-orange authigenic crystals on surface (Figure 11), and about 25 percent have quartz overgrowths.

Tourmaline: Subangular to well-rounded grains, pleochroic in shades of blue, green, brown, and re-brown, to clear. Subangular grains appear to be well-rounded detrital tourmaline cores with overgrowths of authigenic tourmaline. About 50 percent of grains contain small acicular inclusions.

Pyrite: Aggregates of small euhedral crystals, brass yellow in reflected light.

Zircon: Well-rounded light pink, and highly fractured.

Ilmenite-Magnetite: Subrounded grains, all show alteration to leucoxene in varying degrees.

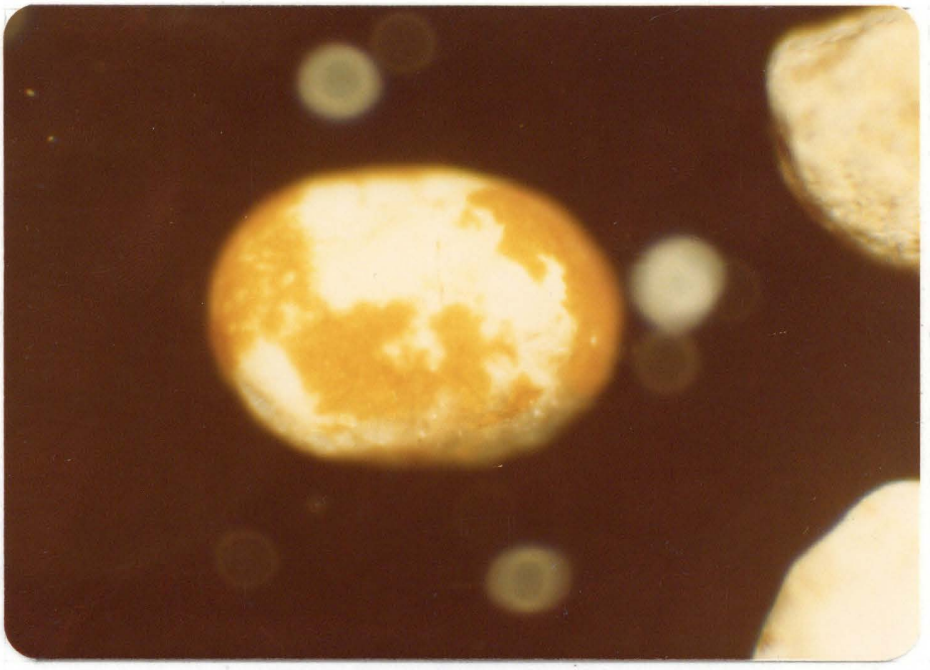
Authigenic grains: Aggregates of red crystals that have extreme birefringence and high refractive indices. About 50 percent of grains are intimately associated with quartz.

Muscovite: Flat grains with rounded outlines and ragged edges, wavy extinction.

Monazite: Well-rounded translucent yellow grains, extensive fractures, waxy luster in reflected light.

II/2-(120) Leucoxene: Subrounded to rounded grains, white in

FIGURE 11



Photomicrograph of leucoxene (white). Note red-orange authigenic crystals on surface. Reflected light, 110X. From unit II/2-(80).

reflected light. About 50 percent of grains have small red authigenic crystals on surface, and about 50 percent have quartz overgrowths.

Tourmaline: Subangular to well-rounded grains, pleochroic in shades of blue, brown, green, and yellow, to clear. Subangular grains appear to be well-rounded detrital tourmaline cores with overgrowths of authigenic tourmaline. About 10 percent of grains contain acicular inclusions and about 20 percent are pleochroic in more than one color.

Pyrite: Aggregates of small euhedral crystals that show an iridescent tarnish in reflected light.

Zircon: Subangular to well-rounded (Figure 12) colorless grains. Well-rounded grains are highly fractured, whereas subangular grains are not fractured and have remnant rerminations.

Ilmenite-Magnetite: Subrounded grains, black in reflected light. Grains show varying degrees of alteration to leucoxene.

Rutile: Well-rounded elongate grains, bright red, with an adamantine luster in reflected light. About 25 percent of grains have small amber prismatic crystals on surface.

Authigenic grains: Aggregates of red, amber, and colorless crystals with extreme birefringence and high refractive indices. About 75 percent of grains contain leucoxene in varying amounts.

Muscovite: Flat grains, 50 percent have an

FIGURE 12

Photomicrograph of zircon. Note roundness and fractures. Crossed nicols, 250X. From unit II/2-(120).

irregular outline and 50 percent have a rounded outline. Grains have a wavy extinction.

Garnet: Subangular highly fractured light pink completely isotropic grains.

Monazite: Well-rounded translucent yellow grains. Grains are highly fractured and have a waxy luster in reflected light.

II/4-(80) Leucoxene: Rounded grains, white in reflected light. About 50 percent of grains have quartz overgrowths, and about 10 percent contain small acicular inclusions.

Pyrite: Aggregates of small euhedral crystals, brass yellow in reflected light. About 70 percent of grains have sand grain impressions.

Hematite: Subangular platy grains. Grains are red-brown in reflected light and translucent at edges.

Zircon: Well-rounded light pink highly fractured grains.

Rutile: Well-rounded elongate grains, bright red, and an adamantine luster in reflected light.

Authigenic grains: Aggregates of yellow and dark red crystals, have extreme birefringence and high refractive indices. About 50 percent of grains contain traces of leucoxene.

Biotite: Flat heavily altered (chloritized?) grains, irregular outlines and ragged edges.

Muscovite: Flat grains with rounded outlines and ragged edges.. Grains have a wavy extinction.

II/4-(120) Leucoxene: Rounded grains, white to light brown in reflected light. About 50 percent of grains have clusters of red and yellow authigenic crystals on surface, and about 10 percent have quartz overgrowths.

Tourmaline: Subrounded to rounded grains, pleochroic in shades of blue, brown, and green, to clear. About 50 percent of grains contain clusters of acicular inclusions.

Pyrite: Aggregates of small euhedral crystals, brass yellow in reflected light. About 30 percent of grains are completely enclosed in quartz.

Zircon: Well-rounded light pink to colorless highly fractured grains.

Hematite: Subangular platy grains, red-brown in reflected light and translucent at edges.

Rutile: Well-rounded elongate grains, red-brown, and an adamantine luster in reflected light (Figure 13).

Authigenic grains: Aggregates of small red and amber crystals. Crystals have extreme birefringence and high refractive indices. About 20 percent of grains are completely enclosed in quartz.

Ilmenite-Magnetite: Subrounded grains, black in reflected light, and altered to varying degrees to leucoxene. About 30 percent of grains have quartz overgrowths.

Muscovite: Flat grains, irregular to rounded outlines and ragged edges, and have a wavy extinction.

FIGURE 13

Photomicrograph of detrital rutile. Note red-brown color, adamantine luster, and elongate form. Reflected light, 110X. Form unit II/4-(120).

II/5-(80) **Leucoxene:** Subrounded to rounded grains, white in reflected light. About 30 percent of grains have clusters of red authigenic crystals on surface.

Tourmaline: Rounded to well-rounded grains, pleochroic in shades of brown and green. About 20 percent of grains contain acicular inclusions.

Pyrite: Aggregates of euhedral crystals, brass yellow in reflected light. About 75 percent of grains have sand grain impressions.

Zircon: Well-rounded colorless highly fractured.

Hematite: Subangular platy grains, red-brown in reflected light and translucent edges. About 30 percent of grains are intimately associated with quartz.

Authigenic grains: Aggregates of red and yellow crystals, have extreme birefringence and high refractive indices. Grains contain leucoxene in varying amounts.

Ilmenite-Magnetite: Subrounded grains, black in reflected light. Grains have small patches of leucoxene on surface.

Garnet: Subangular amber highly fractured completely isotropic grains.

II/5-(120) **Leucoxene:** Rounded grains, white in reflected light. About 25 percent of grains have quartz overgrowths and about 40 percent have clusters of red authigenic crystals on surface.

Tourmaline: Rounded to well-rounded grains, 30 percent showing remnant prismatic form. Grains are pleochroic in shades of green and brown, and

about 20 percent contain small acicular inclusions.

Zircon: Subangular to well-rounded colorless and light pink grains. Well-rounded grains are highly fractured, whereas subangular grains have few.

Hematite: Subangular platy grains, red-brown in reflected light and translucent at edges.

Rutile: Well-rounded elongate grains, bright red and amber, and an adamantine luster in reflected light.

Ilmenite-Magnetite: Subrounded grains, black in reflected light. All grains show alteration to leucoxene in varying amounts.

Garnet: Subangular pink highly fractured completely isotropic grains.

Authigenic grains: Aggregates of amber and red crystals. Crystals have extreme birefringence and high refractive indices. Grains contain small amounts of leucoxene.

II/6-(80) Leucoxene: Rounded grains, white to light brown in reflected light. About 70 percent of grains have quartz overgrowths and 30 percent have clusters of red, amber and colorless authigenic crystals on surface.

Tourmaline: Rounded to well-rounded grains, pleochroic in shades of brown, green, and blue. About 25 percent of grains contain small acicular inclusions.

Pyrite: Aggregates of euhedral crystals, brass yellow in reflected light, and about 50 percent of grains have sand grain impressions.

Zircon: Well-rounded colorless highly fractured grains.

Rutile: Well-rounded yellow and red grains, with small presmatic authigenic crystals and leucoxene on surface.

Ilmenite-Magnetite: Subangular to subrounded grains, black in reflected light. About 30 percent of grains have small amber, prismatic authigenic crystals and leucoxene on surface and about 25 percent have quartz overgrowths.

Monazite: Well-rounded yellow grains, waxy luster in reflected light.

Muscovite: Flat grains with irregular to rounded outlines and ragged edges. Grains have a slight green tint and a wavy extinction.

Authigenic grains: Aggregates of red and colorless crystals. Crystals have extreme birefringence and high refractive indices. About 25 percent of grains are enclosed in quartz.

II/6-(120) Leucoxene: Rounded grains, white to light brown in reflected light. About 50 percent of grains have quartz overgrowths and about 25 percent have clusters of red and colorless authigenic crystals on surface.

Tourmaline: Subangular to well-rounded grains, pleochroic in shades of brown, green, and blue. Subangular grains appear to be well-rounded detrital tourmaline cores with overgrowths of authigenic tourmaline. About 30 percent of grains contain small acicular inclusions.

Pyrite: Aggregates of euhedral crystals. Grains have an iridescent tarnish in reflected light due to oxidation.

Zircon: Well-rounded light pink highly fractured grains.

Rutile: Well-rounded elongate grains, bright red with an adamantine luster in reflected light.

Ilmenite-Magnetite: Subrounded grains, black in reflected light, with leucoxene on edges.

Authigenic grains: Aggregates of red, amber and colorless crystals. Crystals have extreme birefringence and high refractive indices. About 30 percent of grains are intimately associated with quartz.

II/7-(80) Leucoxene: Rounded grains, white in reflected light. About 50 percent of grains have clusters of small amber authigenic crystals on surface, and about 30 percent have quartz overgrowths. (Figure 14).

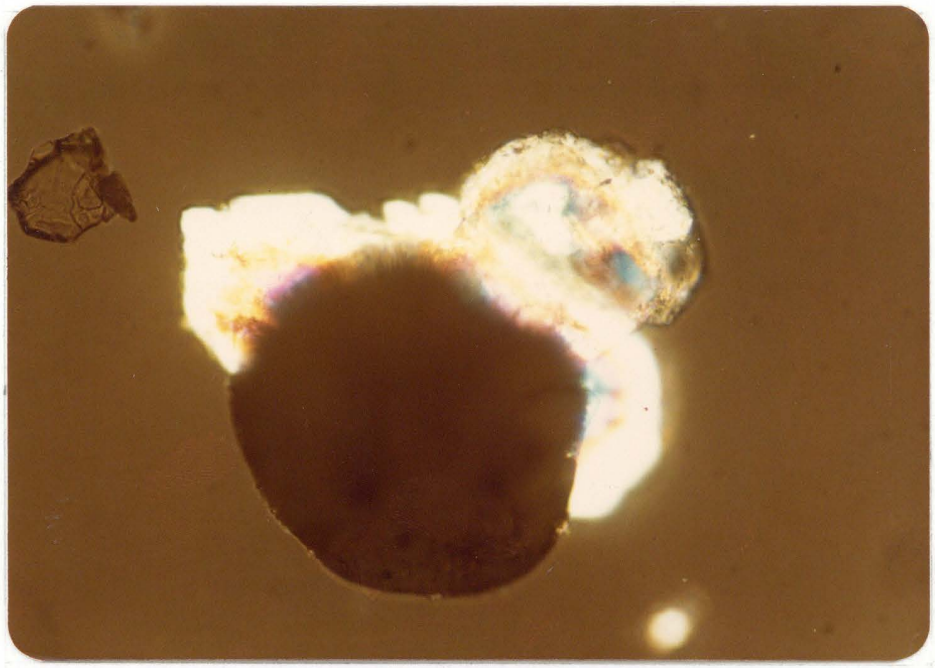
Tourmaline: Subrounded grains, pleochroic in shades of brown, green, and blue, to colorless. About 20 percent of grains are pleochroic in two or more colors, and about 25 percent contain small acicular inclusions.

Pyrite: Aggregates of small, euhedral crystals, brass yellow in reflected light.

Hematite: Subangular platy grains, red-brown in reflected light and translucent edges.

Zircon: Subrounded colorless moderately fractured grains with remnant terminations.

FIGURE 14



Photomicrograph of leucoxene (dark) with quartz overgrowth. Crossed nicols, 250X. From unit II/7-(80).

Ilmenite-Magnetite: Well-rounded grains, black in reflected light.

Garnet: Subangular light pink highly fractured completely isotropic grains.

Rutile: Well-rounded grains, bright red and an adamantine luster in reflected light.

Authigenic grains: Aggregates of amber crystals. Crystals have extreme birefringence and high refractive indices. About 50 percent of grains are enclosed in quartz (Figure 15).

II/7-(120) Leucoxene: Rounded grains, white in reflected light. About 70 percent of grains have quartz overgrowths and about 40 percent have clusters of red authigenic crystals on surface.

Tourmaline: Rounded to well-rounded grains, about 10 percent showing remnant prismatic form. Grains are pleochroic in shades of brown, green, and blue. About 20 percent are pleochroic in more than one color. About 25 percent of grains contain small acicular inclusions.

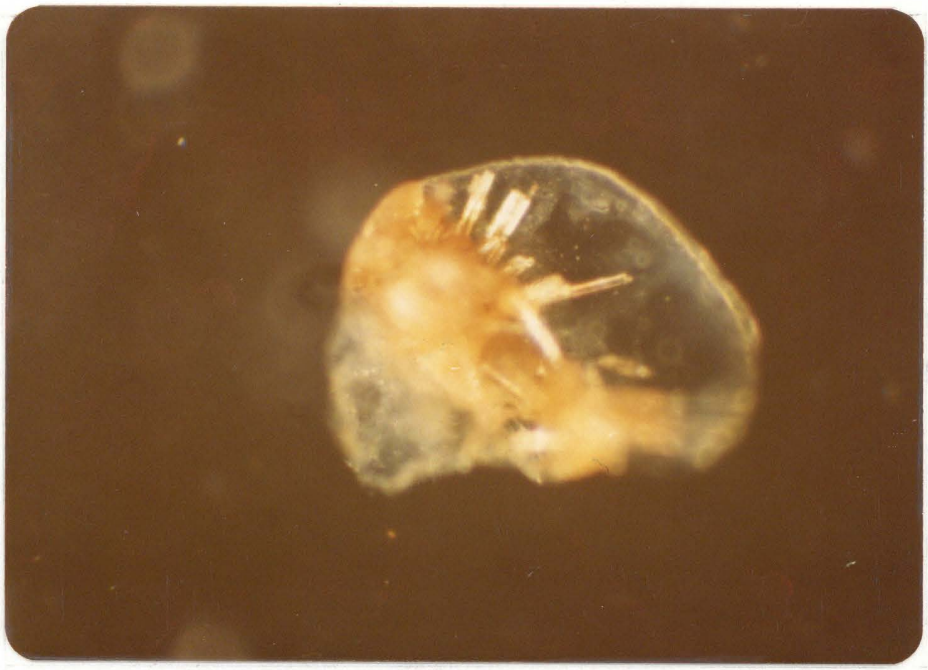
Pyrite: Aggregates of small euhedral crystals, brass yellow in reflected light.

Zircon: Rounded light pink to colorless moderately fractured grains.

Hematite: Subangular platy grains, red-brown in reflected light, and translucent at edges.

Ilmenite-Magnetite: Subrounded grains, black in reflected light, with small amber authigenic crystals and leucoxene on surface.

FIGURE 15



Photomicrograph of an 'authigenic grain'. Note quartz overgrowth and prismatic form of crystals. Reflected light, 250X. From unit II/7-(80).

Rutile: Well-rounded grains, red, with an adamantine luster in reflected light. About 50 percent of grains have leucoxene on surface.

Authigenic grains: Aggregates of small amber crystals. Crystals have extreme birefringence and high refractive indices.

Garnet: Subangular light pink highly fractured completely isotropic grains.

Muscovite: Flat grains with irregular outlines, and ragged, iron oxide stained edges.

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